XIII.—*Experimental Researches on the Lifting Power of the Electro-Magnet.* Part I. By the Rev. T. R. Robinson, D. D., Member of the Royal Irish Academy, and of other Scientific Societies.

Read June 14, 1852.

As soon as Oersted's great discovery had led to the construction of electro-magnets, high expectations were formed that they might afford a motive power as energetic and more economical than the steam-engine. The prodigious force which they manifest when excited by even a feeble current, and the power of annulling or reversing it in an instant, might seem to justify the hope; and an immense amount of inventive talent has been expended in attempts to realize it. These attempts, however, have shown that electro-magnetic engines can scarcely ever be either a cheap or a very efficient source of power. Electricity is now known to have a definite mechanical equivalent; the zinc and acids required to produce it are more costly than the coal, which will evolve isodynamic heat; and the hitherto contrived methods of converting electro-magnetism into moving force involve much more loss than the mechanism of the steam-engine does in respect of heat. I may add, that the great magnetic force which I have referred to exists only in contact; on the least separation of the keeper it decreases rapidly, not merely because magnetic force follows the law of the inverse square of the distance, but because that separation destroys in a very great degree the actual magnetism of the magnet. It must, however, be kept in mind that there are many cases where economy and intensity are of less consequence than facility of application and convenience; in which, therefore, the electro-magnetic engine deserves a preference even for industrial purposes, and much more for the work of the experimental physicist, although its action may be more costly. In particular, the absence of all danger, and perfect quiescence when not put in

action, and the capability of being moved to any locality where a couple of wires can be led from its battery, deserve special consideration. Such views several years ago induced my friend, Mr. T. F. BERGIN, to experiment on the construction of a machine suitable to the workshop of the amateur, or the laboratory of the philosopher; and I hope he will at no distant period lay his invention before the Academy. In its progress he occasionally consulted me as to the form and mass of the magnets to be employed; the distribution and kind of wire in their helices; and the intensity of the currents transmitted through them which might be expected to give the highest dynamic effect from a given consumption of materials. On all these points I was surprised to find that there was little or no exact information extant; I therefore determined to look for it myself; and since the beginning of 1848 have given to this object such attention as was permitted by my other avocations. In carrying it out I have derived much valuable aid from Mr. BERGIN, not merely in the contriving and constructing the necessary apparatus, but also in making many experiments which I had not the means of performing. During this period several German physicists have been engaged in similar investigations;* but if I do not deceive myself, neither their results, nor those of Mr. JOULE,† go so far as to make the present communication unnecessary; and I trust it will be found not merely useful to the practical magnetician, but also valuable, as affording data which have been carefully determined, to those, who like Dr. WILLIAM THOMSON, are investigating the theory of magnetic induction.

Before describing my methods of experimenting, a brief account of what occurs in the action of the electro-magnet may make their object more intelligible. If we conceive the cylindric core divided into thin sections perpendicular to its axis, and confine ourselves to the uppermost of them; on passing a current through the helix, its two surfaces will possess opposite polarities, derived mainly from the inducing power of those spires which are in its plane, but also in a decreasing amount from those which are below it. The intensity of these polarities depends on that of the inducing forces and of those which oppose them; the former is known to be proportional to the intensity of the

* Translated by Dr. TYNDALL in the Philosophical Magazine, March, 1851.

† Philosophical Magazine, October, 1851.

electric current and a function of the number and diameters of the spires, but the other is almost totally unknown. It is admitted that these polarities comport themselves as if they were two fluids, each repelling itself or attracting the other inversely as the square of the distance, and becoming latent when permitted to unite; we might, therefore, suppose that under the influence of the excited helix, they will separate until the increasing repulsion of themselves, and attraction of each other, balance its influence. But there is yet another force which prevents this separation from proceeding quite so far; it is called the coercive force, and may be described as a resistance which the molecules of iron present to any alteration of their polar condition, whether the change be union or separation of polarities. The first of these will be as the polarity, the last some function of it, of which, I believe, nothing is known. Let now a second section be placed below the first, and in contact with it; it will be excited to an equal intensity; but the heteronymous polarities partially neutralize each other at the contact surface, and the remaining two being at twice the former distance have less power to oppose the induction of the helix. Therefore it will produce a still greater separation of the polarities, and so on, till the helix is filled with these sections. For this we may evidently substitute a solid bar; the intervals between its molecules being analogous to the surfaces of contact, and as evidently it can be shown that the extremities of the bar will exhibit opposite polarities, whose intensity gradually decreases towards the centre till it vanishes at that point. If now a keeper of the same section be placed on one extremity of the magnet, suppose the Boreal one, it will also become a magnet, and its Austral polarity will neutralize much of the Boreal of the other; the action of the helix will therefore evolve a still higher degree of magnetism in the latter, till a new equilibrium of forces is attained. In this instance, however, we can measure the new polarity, for it is proportional to the force with which the keeper is attracted by the polar extremity of the magnet. On the same principles the development of the magnetism will be carried still higher if the remote extremity of the keeper be connected with the Austral extremity of another magnet; and it will reach its maximum if the remaining poles of the two magnets be united as in the ordinary horse-shoe, and thus a magnetic circuit be completed. In this case there would be scarcely any free magnetism evident, and the forces which oppose H, the action of the helix

on each molecule, are the coercive force C; and the differences of polar attractions across the molecule itself M, and across the intervals between it and those which adjoin it D. At the contact of the keeper this interval must be far greater than in the continuous iron; and the constant of attraction may also be different, but I think the attractions will be in a constant, perhaps an assignable, ratio.* If in this state of things the current in the helices be stopped, the polarities of the molecules tend to re-unite by the forces $M-D$, and are prevented by the force C, which now maintains the magnetic state as it opposed its production. As M must be always greater than D, and, as I have said, proportional to it, the magnetism must sink until $M-D=C$, and then remain permanent. It has long been known that the keeper of an electro-magnet adheres to it with considerable force when the current ceases; but I am not aware that the meaning of this fact has been interpreted, or measures of it taken. Now lifting the keeper, D is destroyed at the polar surfaces, and the forces are $M-C$, so that the magnetism will decrease till $M=C$, but will not necessarily vanish even in this case.

It is not my intention to go further into the theory of electro-magnetism, which I hope will be fully developed by the able geometrician to whom I have already referred; and I merely call attention to these elementary principles of it for the purpose of indicating the sort of information which I have endeavoured to obtain, and the way in which it seems to bear on these molecular forces.

The power of an electro-magnet may be examined either by measuring the force required to detach a keeper from its poles; secondly, by observing its attraction of a mass of iron at a small distance; or thirdly, by its deflection of a magnetic needle. The second of these methods appears to me objectionable, from the complication introduced by the rapid curvature of the lines of magnetic action near the poles, and from the great diminution of the forces by a very small interval; this is even more felt in the third, as the needle must be placed at a very considerable distance from the magnet. In both the varying distribution of the magnetism must be taken into account, and neither of them seems

* The contact will be closer when the attraction is powerful, and therefore the adhesion of the keeper something greater than what is due to the mere intensity of the magnetism, but I do not know whether this effect is appreciable.

to offer any mode of distinguishing between the forces *M*, *D*, and *C*. The first may be perhaps less accurate as to individual measures, or at least requires greater care and more numerous repetitions than the method of deflection ; but these are probably more than compensated by the magnitude of the quantity to be measured. In applying it I have examined—

1. The relation between a magnet's power and the intensity of the current passing through its helices.

2. The effect of varying the number of spires in the helices and their distribution on the magnet.

3. The change produced by varying the unexcited portion of the magnetic circuit.

4. The difference between electro-magnets of iron and those of steel ; and

5. The influence of the length and diameter of the magnet.

The first of these is the subject of the present communication, reserving the others for another opportunity.

The apparatus which I used in making these experiments consists of an electro-magnet, a weighing apparatus, and the instruments for measuring and regulating the exciting current, each of which requires some notice.

1. The magnet consists of two cylinders of iron (the softest and most homogeneous that I have ever seen), each twelve inches long and two in diameter. They were made hollow, as from BARLOW's experiments I had imagined that the central portion added little to the effect ; and I purposed to experiment at temperatures above boiling water, by introducing heaters in these cavities. I find that in this I was mistaken,* but the results are merely reduced in proportion to the transverse section, or as 3 : 4, the cavity being one inch diameter. The cylinders are screwed, with their axes 6 inches apart, into a base of the same iron, 2 inches deep, and $2\frac{1}{4}$ broad ; together they weigh 26 lbs. The keeper is a rectangular prism, the same size as the base, weighing 7 lbs. It was planed and fitted so carefully, by scraping, to the polar surfaces of the cylinders, that it all but adheres to them by atmospheric pressure ; and was then fitted with guides, so as always to insure uniformity of contact.

* Mr. BERGIN, with my helices on a solid magnet of the same dimensions, obtained with a current = 1·0117, a lift of 670·8 lbs. This magnet, with the same current, gives 509·2 ; the numbers are as 4 : 3·03.

The helices are made of lapped copper wire, No. 12, or $\frac{1}{9}$ inch diameter, coiled in four layers on mahogany bobbins, $2\frac{3}{8}$ diameter, and 10·9 long. The two have 638 spires, and 483 feet of wire; each layer being well soaked with lac varnish. I used wood for these bobbins, to prevent the magnet from being much heated when powerful currents are employed, but in all subsequent helices used copper, as the wires were sometimes so hot that I feared for their covering.* The external diameter of the helices is 33 inches.

2. The weighing apparatus is shown in the wood-cut. It consists of a strong oak table, T, 32 by 16 inches, and 2 inches thick, in which are, inlaid and secured by strong wood screws, two pieces of $\frac{3}{8}$ boiler-plate. On one of these is fixed the magnet by a strong bolt tapped into the centre of its base B, and set

* On one occasion, with metal bobbins, the magnet and its keeper were heated 35° in 70 minutes.

vertical by adjusting screws not shown in the figure.* The same iron plate bears the pillar P, also iron, 27·5 inches high, 2 and $1\frac{1}{4}$ diameter at its extremities, firmly screwed below, and steadied by oblique braces of $\frac{3}{4}$-inch round iron (not shown), bolted to the iron at the other end of the table. This bears in rings of hard steel the fulcrum knife-edge of the lever L, which is of spring-steel, $\frac{5}{8}$ thick, 3 deep, tapering to 2 and $1\frac{3}{4}$. Its arms are 21 and 3·5. Its short arm carries by knife-edges the cylinder H, in which is tapped a strong steel screw passing through a hole in the centre of the keeper K, and bearing it by a hemispheric head fitted in a corresponding cavity. The other arm is similarly linked by EE′ to a second lever L′, whose fulcrum is in the pillar P′ 12 inches high. Its arms are 10 and 1 inches; and at its outer extremity it carries the scale dish S. A slit in the direction of its length enables it to act as a steelyard, by shifting along it small weights suspended by a loop of fine iron wire; and for this object it has a division from $1^{i}.9$ to $9^{i}.5$. The whole apparatus (except the scale) is counterpoised by attaching to L a piece shown in plan, fig. 2, by the screw *s* and the steady pin *t*. The box O contains shot, and the ball R, which is tapped on a fine screw, makes the adjustment exact.

The mode of using this instrument is easily understood. When the magnet is excited, and weights nearly equivalent to its lift are placed in the scale, the screw of the keeper must be turned till a mark on L′ stands at the index I. This index, which is hinged to P, so that it can be turned out of the way, shows when the lower edge of the slit in L′ is horizontal. Then a check-nut on the screw must be turned into firm contact with H, to preserve this adjustment

* This arrangement of the magnet did not admit of its being removed, and replaced with the requisite precision; and latterly it was changed for one which Mr. Bergin contrived to meet this difficulty. A very strong rectangular frame of brass is secured on the table, 2 inches deep, and able to receive within it the base of the magnet, with an inch play all round. The magnet is slightly excited, so that it may hang freely from its keeper in this space. Then steel screws tapped in the brass, one in front, two behind, and two at the ends of the frame, are brought up so as to pinch the base equally, and thus I am certain that the pull which separates the keeper from the magnet will always be direct. This I find acts most satisfactorily.

during a series of measures. The least of the sliding weights is now hung to its loop and cautiously moved, till either it lifts the keeper, or arrives at the end of the division. In the latter case it is changed for a heavier. If none of them overcome the magnet, a scale weight, equivalent to the greatest moment of the last of the steelyard weights, is placed in the dish, and so on. Those which I use are 0·1 lb., 0·2, and 0·6 for the steelyard; the others are 0·5, 1, 2, 4, 7, and 14; the dish also = 0·5. They were carefully verified by a set of grain-weights belonging to me, and another of Professor STEVELLY. The leverage of the machine was determined with equal care. By means of the above weight and a balance, for the use of which I am indebted to my friend Mr. MALLET,* two of 28 lbs. and two of 56 were verified. Suspending them to the keeper, I found the weights required to counterpoise 56, 112, 168, and 199 lbs., and obtained their ratio = 59·730. In these trials additions to the load of 0·031, 0·046, and 0·094 lb. were easily detected; an error of about 1 lb. in the ton.

A machine of this kind is of course not expected to equal the accuracy of an ordinary balance; but for the work which it has to do it is far preferable on two accounts. To lift the keeper by weights equal to its attraction would be very dangerous, for the sudden descent of 8 or 9 cwt. would cause a fearful concussion; while the fall of its equivalent, 15 on the pad T′, is scarcely felt. Besides, when the separation is nearly attained, the most delicate manipulation is necessary; and it is far easier to avoid jar in sliding a light weight, than in placing in a scale one sixty times as heavy. But in fact the force to be measured is itself fluctuating to an extent which far passes any errors of the weighing.

3. I have measured the intensity of the voltaic current by a tangent rheometer; and this mention of it might suffice, were it not that even in an instrument so well known the details of its use are not without value, and that its results cannot be duly compared to those of another without a distinct knowledge of its individuality. I prefer it to the one described in a former commu-

* It is the smallest of those mentioned in his Report to the British Association on the Corrosion of Railway Bars; when loaded with 56 lbs. in each scale it turns decidedly with three grains. All these comparisons were made by the method of double weighing.

nication,* as including a wider range, and being independent of the intensity of its needle's magnetism. Its circular conductor consists of five copper rings, each 0·5 broad and 0·05 thick, the innermost of which has 16 inches internal diameter. This is commonly used alone, but the others can be combined with it. The connectors descend from the nadir of the rings within the wooden stem which supports them, pass through its base (which is provided with levelling screws), and then, proceeding about 18 inches in the magnetic meridian, turn at right angles, and proceed parallel, and almost in contact, for three feet, to a commutator which connects them with the general circuit. By thus reversing the current, not merely in the rheometer, but also in so great a length of the connectors, I designed to eliminate their influence ; and experience shows that such a precaution is quite necessary. Concentric with the rings, and perpendicular to their plane, is fixed a brass circle 9 inches diameter, divided to half degrees, at whose centre stands a point of hard steel, very carefully finished to an angle of 60°.† On this turns a needle $1^{i}.77$ long, $0^{i}.25$ deep, and 0·05 thick ; it has a ruby cap, and pointers of palladium long enough to reach the divisions ; and it weighs altogether 75 grains. It has been shown by WEBER (Poggendorf, vol. lv.) that if the ratio of the ring's diameter to the length of the needle be greater than 4 or 5, the tangent of deflection is proportional to the force. This ratio, however, is too low for high deflections. When it is 4 I find the law fails at 33°, and when 4·8 at 50. In this rheometer it is 9. As, however, it was necessary to ascertain whether the influence of the connectors was injurious, I at the same time examined its sufficiency by the voltameter, and found for 28 angles from 20° to 75°,‡ that the tangents are *exactly* as the quantities of mixed gases evolved in a given time, supposed dry, and at the normal temperature and pressure. The factor by which the tangent gives the current force F depends on the unit assumed for that quantity. WEBER, in the memoir referred to, uses one derived from the intensity of terrestrial magnetism at the

* Transactions of the Royal Irish Academy, vol. xxi. p. 303.

† It was formed by traversing it while rapidly revolving in the drill apparatus of a slide-rest, inclined at 30° along the surface of a cylindric lap also rapidly revolving, and charged first with very fine emery, and then with crocus. It bears examining with a power of 120 diameters, and is far more perfect than any point which I have seen in a theodolite or compass.

‡ The greatest which 18 Groves' could produce with the voltameter.

place of observation, a quantity variable in itself, and by no means easy to ascertain. Dr. W. THOMSON has more recently proposed* one expressed in terms of the mechanical effect to which the current is equivalent; which, however, must be regarded as a scientific conception, rather than of practical use. A standard, to be available, must be of easy access and application, and in these respects I see no reason for preferring any to one which is in frequent use, the electrolysis of water. The most obvious current unit is that which can decompose a grain of water in a unit of time. It seems to me, however, that if a second, or even a minute, be taken as time unit, the values of current will be inconveniently fractional, if an hour, as much too large, and therefore I take five minutes. Adopting this, all that is required to make these rheometers speak a given language is, to note the seconds in which a known volume of the gases is evolved, and reduce it to that due to 300 seconds; to compute its normal volume G by means of the formulæ in treatises of Pneumatics, and measure carefully the deflection ϕ', then we have

$$m = \frac{G \times \text{cotan}\,\phi}{\log^{-1}(0{\cdot}89310)};\ F = m \times \tan\phi;$$

the experiments for which can be completed in a single day.

Both ends of the needle are read with direct, and again with reversed current, to eliminate excentricity and zero errors; the readings are made with a prismatic microscope, and can be depended on to 2′.

The rheostat is used in these experiments merely to equalize the current, and therefore has no necessary connexion with their results; but as in a former communication† I mentioned its peculiar construction, and promised further details, I take this opportunity of stating my conclusion as to its working. As exhibited to the Academy on that occasion, it consisted of a wire of platinum, whose length was varied by raising it out of mercury, while it was cooled by being surrounded with distilled water; and I expected that by measuring the temperature of this latter fluid I might apply the necessary correction for the change of resistance due to the heat evolved by the passage of the current. Unless this be attended to, I am satisfied that no measures can be made

* Philosophical Magazine, 1851; p. 551.

† Transactions of the Royal Irish Academy, vol. xxi. p. 303.

deserving full confidence, and that it is necessary *even with the feeblest transference of electricity*. This especially applies to those methods in which a current is divided between two conductors, and its respective quantities in them are estimated from their relative resistances, previously determined. That relation involves the temperature of each, and varies with the current. In many respects this rheostat was a great improvement on that which I previously used, these probable errors being $0^{i}.16$ and $0^{i}.28$; but I soon found it could not invariably be trusted. Occasionally a film of water would adhere so obstinately to the platinum, that its contact with the mercury did not occur till two inches below the surface of the latter; and this state would continue for several days. A little solution of potassa lessened this tendency, but made the water too good a conductor; I therefore abandoned the mercury in that part of the instrument, and made the contact by a spring clip of platinum. This change enables me to use a wire of palladium instead of platinum; the former resisting twice as much with the same section, and, what is more important, varying its resistance ten times less by a given change of temperature; being, in this respect, the lowest of all the metals which I have examined. These alterations have improved the accuracy of the rheostat, its probable error being now only $0^{i}.06$. The wire is $\frac{1}{43}$ diameter, and its range 15 inches, read to $0^{i}.01$, by a vernier.* If greater resistance be required, 19 equivalents of the same wire, also immersed in water, can be added to the circuit. I wish I could give some more definite statement of this wire's resistance than is contained in the mention of its diameter, for that alone is not sufficient. Platinum wire I find, even when drawn in a gemmed hole, and heated white hot after its passages, resists unequally in different parts of the same piece,—much more may different specimens be expected to differ. A tolerable approximation to it, however, is given by the fact, that if we use the current unit just described, the intensity (or the electro-motive force of the contact theory) of a Groves' cell, determined by the tangent rheometer, = 47·282 inches of this wire.†

Another measure (which I hope may ultimately prove an accurate one) is afforded by the electrolytic intensity of water (the imaginary polarization of

* Equal to 970 inches of $\frac{1}{18}$ copper wire.

† Mean of the last 20 I observed, the greatest being 48·675, the least 45·345.

electrodes of the contact theory). As I have formerly shown, it varies by heat. I assigned 0·04986 as the change for 1° Fahr., but this value was obtained by dividing the current, and without means of correcting the rheostat for temperature. I have since obtained by better methods—

$$e \text{ at } 60^\circ = 62{\cdot}229, \quad \text{change for } 1^\circ = 0{\cdot}06735.$$

It is not affected by the quantity of sulphuric acid mixed with the water to increase its conducting power, being almost identical whether this be $\frac{1}{9}$ or $\frac{1}{90}$ of the electrolyte. Nor is it (within very wide limits) by the size of the electrodes; being the same when they oppose surfaces of 19 square inches (the size of the platinum in the battery), of 3, or of 0·75, the intensity of the battery being given.

But there is a change, real or apparent, depending on that intensity. The value above given was obtained with two Groves'; with three it is 69·137 at 60°, and with four 75·052. It is my present belief that this seeming increase is caused by two things: by the internal resistance of the cells decreasing in consequence of being heated by the current, and by the rheostat wire being hotter within than at its surface. The thermometer immersed in the water gives merely the latter temperature, and therefore the resistance correction is too small.* This, however, I hope soon to be able to determine.

After this long preface (which I hope will not be useless to any one who may engage in these or similar researches), I proceed to state in the following

* Taking the equation

$$m \tan \phi = F = \frac{E}{R+r},$$

and introducing a resistance ρ, which produces the deflection ϕ',

$$E = \frac{m(\rho + dR)}{\cot \phi' - \cot \phi},$$

dR being any change of the cells' resistance. Introduce now the voltameter, and a similar equation gives $E - e$. Now if the wire be hotter than we reckon, we use a value of ρ less than the truth, $E - e$ is therefore too little, as we compute it; but E, as separately determined, is also too little, nay, even more so, because the current is stronger when the voltameter is not in circuit. Therefore e will be too great. To obtain access to the truth, it will be necessary, first, to determine the law of the cell's resistance as connected with its temperature; and secondly, to measure the wire's temperature not by an immersed thermometer, *but by its own expansion.*

Table my results, subjoining an explanation of each of its columns, and any miscellaneous facts which could not be easily tabulated.

TABLE.

No.	Obs.	F	T	L at 60°.	$\frac{dL}{dF}$	λ	Λ
1	10	6·8528	78°·1	775·24	. .	4·66	131·81
2	10	5·2015	85·4	722·70	20	4·26	136·34
3	10	4·6566	94·2	713·79	31	4·77	131·31
4	10	3·9366	65·1	677·00	50	5·46	125·51
5	15	3·5843	66·0	659·28	42	4·79	131·74
6	10	3·1303	72·4	645·14	32	5·52	131·07
7	15	2·5496	67·9	632·72	45	5·60	128·31
8	10	2·1769	65·5	610·02	78	4·30	130·80
9	10	1·8876	63·9	588·07	75	4·65	126·10
10	19	1·5384	62·7	568·51	99	4·74	. . . .
11	15	1·4107	61·5	553·81	102	4·56	134·16
12	20	1·2565	63·7	540·61	101	4·60	128·50
13	25	1·1071	62·9	521·12	128	4·87	131·41
14	25	0·9589	62·3	499·80	180	4·41	130·39
15	10	0·7909	62·3	462·53	264	5·77	131·14
16	15	0·6272	61·8	412·52	305	4·37	125·71
17	10	0·5482	62·0	388·42	340	4·59	124·88
18	10	0·4693	61·7	358·81	492	4·96	127·29
19	10	0·3921	62·0	312·04	638	4·38	116·12
20	10	0·3145	61·1	259·95	735	4·53	110·10
21	10	0·2340	61·1	195·49	799	5·06	90·78
22	10	0·1565	62·2	133·67	928	4·87	77·49
23	10	0·1164	60·2	93·79	1028	4·36	62·37
24	10	0·0794	59·2	54·61	1029	4·04	37·50
25	10	0·0389	59·3	14·18	621	4·12	10·08
26	50	0·0000	. . .	4·44	41	. . .	. . . .
27	10	− 0·0389	58·8	+ 2·19	49	+ 2·75	+ 3·28
28	5	− 0·0798	59·5	− 2·81	134	+ 3·00	− 3·67
29	5	− 0·1162	62·8	− 29·30	1148	− 1·81	− 11·19
30	5	− 0·1551	60·0	− 91·26	1503	− 3·79	− 47·77
31	5	− 0·2343	62·1	− 166·72	926	− 4·20	− 77·58
32	4	− 0·3140	62·1	− 238·46	776	− 4·69	− 92·76
33	5	− 0·3925	64·7	− 289·81	735	− 4·49	. . . . .
34	3	− 0·4707	61·2	− 353·64	. . .	− 6·49	− 114·39
35	5	− 0·6243	60·2	− 404·64	. . .	− 3·64	. . . . . .

The second column of this Table contains the number of experiments on which the value of L given in the fifth is based. In general, two sets of five each were taken on separate days, and if they were in close agreement this was

thought sufficient. But it sometimes happens that though each set is perfectly consistent, the two differ as much as 20 lbs., which occurs especially when the magnet's lift is about half its maximum, at which point the coercive force of the iron seems to make some abrupt change. In these cases other sets were taken, till from the uniform spread of the differences I felt satisfied that I had obtained a fair average.

The third column, headed F, contains the values of the currents expressed in the unit which has been described above. It must be remembered, however, that they act on 638 spires. I consider them true to 0·001 at least of their assigned amount. The negative sign indicates that in these instances the direction of the current is reversed in the helices.

The fourth column gives T, the temperature of the magnet, as shown by a thermometer dipped in mercury, which filled the upper inch of the cavity in the northern cylinder of the magnet; at first both cylinders were tried, but this was found useless. It is necessary to know the temperature, for the force of electro-magnets, as of common ones, varies with it. To investigate the correction, 40 feet of leaden pipe, $\frac{3}{8}$-inch external, and $\frac{1}{4}$ internal diameter, were coiled on helices, containing 316 spires of the same wire used in the others, but coiled on tin tubes. These worms had each 25 turns; they were covered with thick cloth, and connected by a tube of vulcanized caoutchouc with a small boiler, so that a current of steam could be passed through them, and the condensed water escaped from their open extremity.* As the keeper and base (which were also covered with cloth) presented much cooling surface, the temperature could not be maintained above 180°, but could be kept very steady. The lift of the magnet being then determined, the magnet was left to cool, and the observation was repeated at the ordinary temperature, and with the same current as nearly as could be managed. As I was not aware of any reason for supposing that the effect of temperature changes its law under that of boiling water, I assumed the change to be as the temperature, or, L being the lift at 60°,

$$l = L \times \{1 + \tau(T - 60)\}.$$

* To the last it was turbid with sulphuret of lead, so that this material cannot be depended on as a conductor of steam.

Hence

$$\tau = \frac{l'-l}{l(T'-T)} + \left\{\frac{l'-l}{l(T'-T)}\right\}^2 \times (T - 60^\circ) + \&c.$$

Then I obtained

$$1. \begin{cases} l' = 461{\cdot}55 \ldots\ldots T = 167^\circ{\cdot}0 \ldots\ldots F = 1{\cdot}5830 \\ l = 480{\cdot}94 \ldots\ldots\ldots\ldots 69{\cdot}1 \ldots\ldots\ldots\ldots 1{\cdot}5868 \end{cases}$$

$$2. \begin{cases} l' = 583{\cdot}04 \ldots\ldots\ldots\ldots 174{\cdot}3 \ldots\ldots\ldots\ldots 2{\cdot}6198 \\ l = 601{\cdot}83 \ldots\ldots\ldots\ldots 70{\cdot}5 \ldots\ldots\ldots\ldots 2{\cdot}6198 \end{cases}$$

$$3. \begin{cases} l' = 646{\cdot}80 \ldots\ldots\ldots\ldots 175.4 \ldots\ldots\ldots\ldots 3{\cdot}5634 \\ l = 661{\cdot}62 \ldots\ldots\ldots\ldots 73{\cdot}8 \ldots\ldots\ldots\ldots 3{\cdot}5761 \end{cases}$$

$$4. \begin{cases} l' = 329{\cdot}39 \ldots\ldots\ldots\ldots 172{\cdot}5 \ldots\ldots\ldots\ldots 0{\cdot}8613 \\ l = 343{\cdot}08 \ldots\ldots\ldots\ldots 69{\cdot}3 \ldots\ldots\ldots\ldots 0{\cdot}8608 \end{cases}$$

Interpolating for the difference of F in each pair,* I obtain from these—

1.	$\tau = -\ 0{\cdot}000385$
2.	. . . $-\ 0{\cdot}000300$
3.	. . . $-\ 0{\cdot}000220$
4.	. . . $-\ 0{\cdot}000385$
Mean, .	$-\ 0{\cdot}000322$

The three first might induce a suspicion that τ diminishes as F increases; but the fourth disproves this; and as the third set was less consistent than the rest, I regard the difference as mere error. I use the value 0·00033.

Subsequent to these experiments Dr. Lloyd has discovered that the inductive power of terrestrial magnetism is *increased* by a small elevation of temperature. Before this came to my knowledge I had applied the wire of these helices to other purposes, or I would have examined the coefficient τ at intermediate temperatures; I have, however, made a similar observation with respect to steel electro-magnets, and suspect it depends on the coercive force bearing a high ratio to the inducing force. In the present instances I do not

* The interpolation was deduced from a special series; these values of L not being comparable to those of the Table, as the helices have only half the number of spires, are of less diameter, and their tin bobbins add something to the mass of the magnet.

think any change of sign occurs: were it otherwise I must have noticed its effect; as in many of these experiments the magnet has been heated by the current above 100°, and an increase of L must have been produced contrary to all my experience. I may, however, have occasion to re-examine the question, and will not neglect it.

The fifth column gives L, the number of pounds required to lift the keeper, obtained by reducing the observed number to 60° by the coefficient τ. It may seem an easy matter to obtain this, but no one who has not tried it will be prepared for the many precautions that are necessary.

1. The utmost stability in the apparatus, absence of tremors, and delicacy of touch, are required. With a heavy lift, when approaching the limit of adhesion, the agitation caused by a step, the shutting of a distant door, or the action of a gust of wind on the building, will determine a break of contact, with a deficiency of 10 or even 20 lbs.

2. These magnets (and it is the case also with permanent magnets) will bear a much greater load if the strain be gradually increased, than if it be applied abruptly, the difference being sometimes 40 lbs. Therefore the weight of the steelyard must be slided along very gradually (and I need scarcely say with cautious handling), and allowed to rest at each step a few seconds, as it were, to let the acting forces adjust themselves. I do not see why this should be, unless, perhaps, the state of tension which is produced favours the development of magnetism, but the fact is very striking; when the keeper is detached and immediately replaced, it will not nearly resist the load, even if that be upheld, and then lowered to its bearing.

3. Time is an important element: I do not think any current which the wire of this magnet can conduct is capable of developing its full power in a few seconds. With the highest power which I have applied it must act for five minutes *at least*, and from $F=0{\cdot}3$ downwards for full fifteen. This has been noticed, though in a far less degree, by Faraday, who observed the circular polarization caused by the action of electro-magnets on dense glass to increase for a minute and a half after making the contact. That, however, is not a very delicate test; and as the poles of his magnet were not connected by a keeper, the molecular excitement must have been far less intense than in this case. As a specimen of this sluggishness of inductivity (which, by the way, is a

serious impediment to electro-magnetic engines), I give the set which first decidedly convinced me of its influence.

Time = 10^m	$L = 205{\cdot}26$	$F = 0{\cdot}2751$
6	191·10	0·2779
13	213 52	0·2655
8	194·05	0·2603
12	207·62	0·2568

The increase of time more than compensates for a considerable diminution of current. I have regulated the duration of each set according to what I conceived to be a sufficient allowance of time.

4. These causes are uniform in their action, and can be avoided or corrected, but there exists another, which is the chief source of error in these experiments, namely, the molecular change which iron suffers when exposed to powerful magnetization. In consequence of this, however pure and soft it may be, it becomes capable of retaining permanent magnetism, *and in the same proportion less susceptible of excitation by its helices.* This magnetism (which I call λ) is variable ; it may, perhaps, be intense while the magnet is excited, but on lifting the keeper it declines rapidly till it attains a certain amount, which is, however, not invariable ; and it always increases during a set, though after a few hours it returns to its ordinary quantity. It, however, occasionally happens that when the magnet has been powerfully excited for many days, its iron becomes disturbed in this respect, and then the values of L fall far short of their legitimate magnitude. In such cases it is best to leave it at rest for a few weeks ; but I have found that if the current be reversed the L becomes higher, and have therefore in many instances performed this for the alternate measures. The results thus obtained are tolerably uniform, but are always less than those given by a magnet that has never been excited, or has been long in repose. With excitation less than what is given to this magnet by a current = 1, this cannot be done, because then it will be seen from the Table that there is a real difference between the L's produced by the direct and reverse currents. One consequence of this change deserves notice, which may be observed in almost every series,—the gradual decrease of the successive measures of a set. Thus in one taken with peculiar care,

Time = 7^m . . .	$L = 661{\cdot}65$ . . .	F kept at 3·5938
7	658·34	
7	648·10	
9	647·44	
8	644·58	

From all this it follows that the values given in this Table can be offered only as a first approximation, but I hope a close one. The negative values imply that the polarity is reversed.

The sixth column contains the factor which gives the change of L due to a small variation of F. It is the coefficient of the first power of the variable in the formula for interpolation when the distances of the values from which it is derived are unequal; and besides its use in correction of results when there are small differences of power, it is given here, because it must be, nearly, what I call it at the head of the column, the first differential coefficient of L in respect of F, and as such may be useful in testing the hypotheses which we form respecting the functional relation of these quantities. Into this inquiry, I have stated that I do not intend to enter, and I will at present merely direct attention to the entire want of proportionality between L and F.

Ascending from No. 26 we find that a current = 0·04 produces a power of 10 lbs.; the addition of a second 0·04 adds 40; of a third, the same; after which the rate of increase goes on decreasing. No. 13 shows that a unit current will excite an L of 500 lbs., and No. 1 that one nearly sevenfold will add to this only its half. The result is even more striking if we consider column 6. Were L as F, the numbers there should be constant; whereas they decrease from 1028 to 20; and were the series continued upwards, must vanish at a certain value of L not very much greater than 800. This leads us to the remarkable conclusion that L cannot exceed a certain magnitude A, however intense the exciting power may be,* and as a necessary inference, that the separation of magnetic polarities has a limit. For if we revert to the conditions of an excited electro-magnet, which I have noticed at the commencement of this memoir, it is clear that at the surface of contact of the keeper we must have

$$0 = aH + bD - cM - eC.$$

* This has been announced by Mr. Joule (Phil. Mag.); it was, however, recognised by me long before I knew of his paper.

Now there is good reason to believe that C has a limit, or, in other words, that the molecules of iron can oppose only a limited resistance to induction; D and M are as L, and therefore if H be infinite, so must the latter also be, unless M too have a physical limit. What that limit is,—whether the expansion of the hypothetic fluid, or the impossibility of exciting vibratory movement beyond a certain extent,—I do not pretend to determine. For this magnet I believe the A to be under 1000 lbs. Secondly, I would call attention to some other facts that seem important. At No. 26 is found 4·44 for L when there is no exciting force, it is the permanent magnetism λ. If we apply a direct current 0·04, it adds to this 9·74; if a reverse, it only subtracts 2·25; L therefore is a function of λ as well as of F. At Nos. 24 and 28 the differences are $+ 50·17$, $- 7·25$; at 23 and 29 still wider asunder, after which they begin to approach, but are not the same exactly till F passes $\pm 0·7$. At $F = 1·24$, the direct and reverse results are identical. It follows from this that the coercive force consists of at least two terms, one changing sign with F, the other depending on the habitual direction of the excitation; the latter is not overpowered completely until $L = \frac{1}{2}A$, and does not vanish even when $L = 0$, as is manifest from Nos. 27 and 28. As a practical deduction, we may infer that in all machines involving the reversion of an electro-magnet's polarity, its excitation should not fall short of this. On the other hand, it should not much exceed it; for the increase of power gained by a given increase of current is constantly lessening, and the consumption of materials augments even faster than the current.

The seventh column gives the value of λ the residual magnetism, which, for reasons already stated, should be known, in order to compare L with any formula. These numbers are given by from six to ten observations; and it will be observed that they do not vary much. When the reverse happens (as in Nos. 4–7) it is evident from the irregularity of the quantity $\frac{dL}{dF}$, that the values of L are discordant from the rest of the series. It will also be noticed, in confirmation of what was stated as to the coercive force, that in No. 28 λ remains positive, although diminished, although L is negative. The highest value of it which I ever got is 8·88, which (the keeper being removed in the mean time) gradually decreased till, after 36 hours, it was permanent at 3·17.

The last column gives Λ, the residual excitation, or the force which the

magnet retains when, after being excited, the current is withdrawn, and it is left with the keeper down, and which I consider to be the phenomenon that promises the most direct information as to the law of the coercive force. This state seems to continue for an indefinite time; at least I have never found any diminution of its intensity after many weeks. Accordingly, in observing it, I have either left it 10^{m} or during the night. It corresponds to the state $M-D=C$. During the previous excitation these forces were of much greater amount, and the force C had aided $M-D$ against H: when the latter is withdrawn, M re-unites a portion of the opposite polarities, and decreases in consequence, so of course does D. As to C, there is some reason for believing that it may in the first instance aid this re-union; and that a certain decrease of M is required to develop the molecular action on which it depends in the opposite direction. If so, it will depend not on the M which co-exists with it, but a previous one. However, we know that it must also soon begin to oppose the force $M-D$. Now it is obvious that if C were constant, the final value of $M-D$, and therefore of Λ, must also be so; if it were proportional to M, Λ would vanish; and if it were in any inverse ratio of it, the differences of L and Λ would lessen as they increased. On inspecting the Table it does appear that all above No. 15 may be considered of the same value, in its mean 130·68: which amounts to this, that the force C cannot arrest the decrease of the magnetism *as long as it exceeds half the maximum A*. Is it constant above this, where, as has been shown, it yields equally to excitation in either direction, or does it merely suffer there some abrupt change of magnitude? For lower values of L it decreases, bearing always an increasing ratio to it; thus in No. 21 it is nearly half, in No. 23 two-thirds; and in the negative values this continues to hold, although, as in the case of L, they are long less than the positive. If, while the magnet be in this condition, we pass through its helices a current that would in the ordinary mode give it a force equal to its Λ, its entire effect is not superadded to the other. Thus I found that, having passed $F=0·9864$, which on this occasion gave $\Lambda=125·18$, if I passed then $F=0·1395$, which would have produced $L=124·46$, I had $L'+\Lambda=169·81$; so that it only added 44·63. This was to be expected from the principles already explained; but I cannot so well explain an experiment which shows that a current which can give $L=\frac{1}{2}A$ produces the same results even if the magnet have residual excitation. If a negative

current be passed, it destroys this condition, unless very feeble, but even then it lessens it; thus 0·0127 reduces Λ from 129·41 to 117·51. I may add, that even the fifteenth of this will excite this magnet, and change its residual magnetism.

While the magnet is thus circumstanced, it shows faint traces of free magnetism; each cylinder having its accustomed polarity at its acting surface, the opposite at its other extremity, and a neutral point in the middle. The ends of the keeper and base have the same polarities as those of the cylinders with which they are in contact. If one cylinder only be excited, the value of Λ is the same as for the two, but the distribution of the magnetism is modified, as might be expected.